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# Reliability analysis for mine blast performance based on delay type and firing time

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ABSTRACT

Mining blasts may be defined as the use of explosive charges in a controlled manner by following a tightly controlled timing sequence according to an assigned firing order. Changes of timing between charges may result in an altered firing order and failure of the blasting sequence, which can cause high vibration levels, poor fragmentation, and/or an undesirable rock mass movement direction. Despite the importance of timing in determining mine blast results, there exists a lack of methodologies or tools with which to assess performance of a complete blast based on delay type and timing sequence. This document applies reliability engineering principles to evaluate the performance of a mine blast. The analyses are based on test results of the accuracy and precision of electronic and pyrotechnic detonators for typical firing times used in a surface coal mine, but may be applied to a variety of mines and timing scenarios.



## 1. Introduction

Reliability is a broad term associated with the ability of a product to perform its intended function. Mathematically speaking, and assuming that a product is performing its intended function at a time equal to zero, reliability may be defined as the probability that a product will continue to perform its intended function without failure for a specified period under stated conditions. Note that the "product" defined in this context could be an electronic or mechanical product, a software product, a process (a mining blast in this case), or a service, Smith [1].

When assessing the performance of blast timing, the current practice indicates that the performance should be evaluated according to the reliability of the individual detonator, e.g. misfire rate, detonator lifetime. However, for a production blast, the analysis should be carried out by taking into account the entirety of the blasting system, meaning all of the detonators involved instead of just one as traditionally performed. In other words, it is necessary to include all interdependent relations in addition to single component reliability. In this paper, the reliability of a mine blast is studied in terms of the success of the timing sequence for the whole production blast and contains the following aspects: (1) Problem definition; (2) Experimental test results of detonator accuracy and precision; (3) Definition of the reliability of a single delay interval; (4) Development of a reliability block diagram for the problem; (5) Reliability analysis for the whole mine blast.

## 2. Problem description

The arrangement used for analysis is based on a particular blast design commonly used at a surface coal mine in West Virginia. However, the general procedure presented in this paper can be employed to any other configuration or type of mining. At this particular mine, it is common to use the timing arrangement shown in Fig. 1a for pyrotechnic detonator use, and Fig. 1b for electronic detonator use.

For the pyrotechnic configuration as shown in Fig. 1a, there are two charges divided by a deck in each hole. A deck is a layer of non-explosive material in a borehole which separates the explosive column into two parts so that two in-hole detonators are required to initiate the explosive charges. In addition to the in-hole detonators, 25 ms delays are used on the surface to ensure each charge is initiated by delay intervals of 25 ms in sequence. The first-row cross section shows the timing arrangement for a row of four holes, which contains eight charges. The plan view of Fig. 1a shows the full timing and initiation sequence if one row is expanded to three rows. In total, there are 24 charges, and the firing time of each charge referenced to time zero is labeled beside the hole. The timing interval between two rows is selected as 200 ms, which renders

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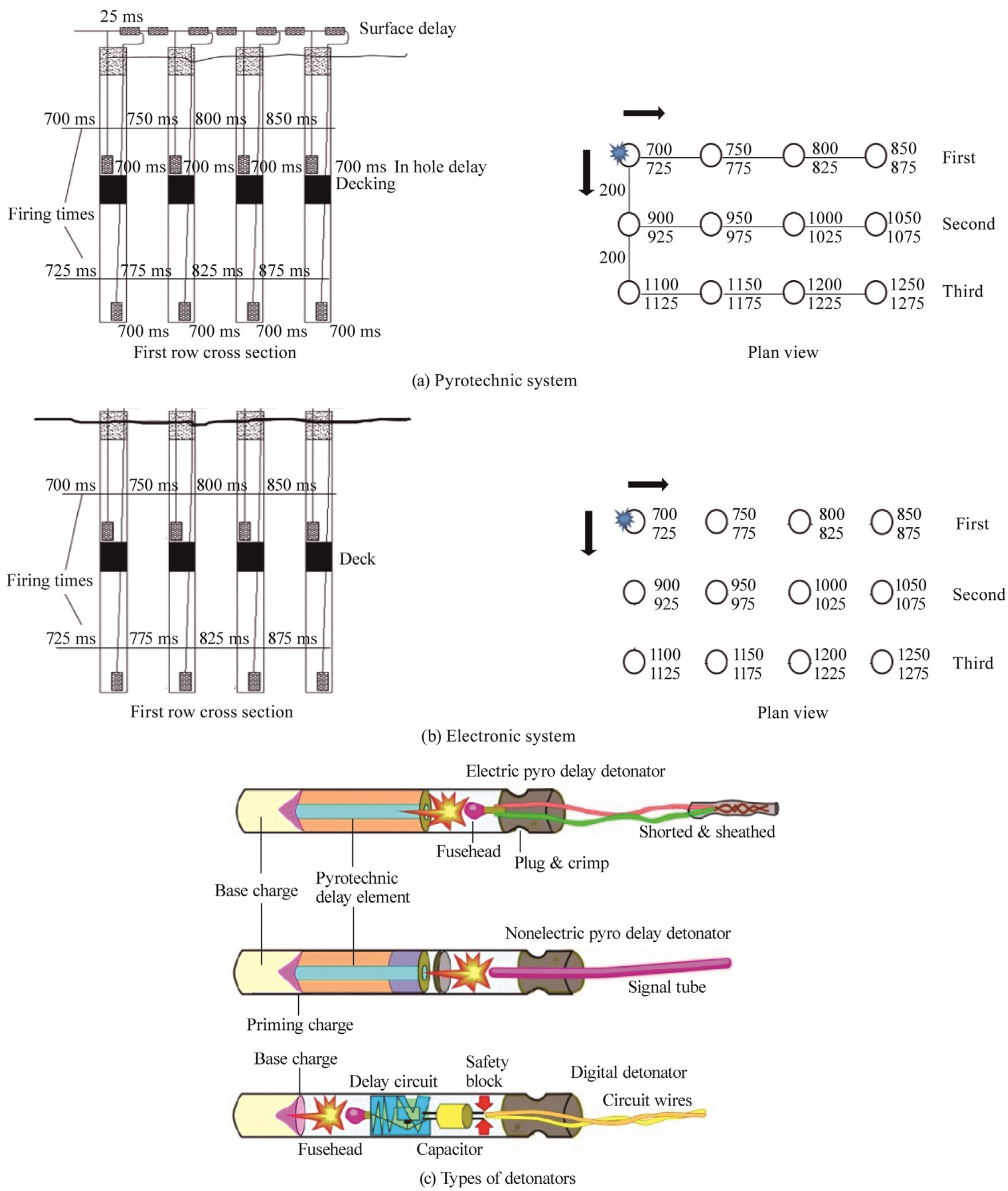



**Fig. 1.** Timing arrangement of multiple holes [2].

the first hole of the second row and the last hole of the first row to be 25 ms apart. The 200 ms interval is created by using two 100 ms detonators in series for this scenario.

Fig. 1b shows the arrangement of the electronic detonator configuration. In this scenario, each electronic detonator receives the firing signal instantaneously and then detonates according to its programmed time. Thus, each electronic detonator detonates independently. The plan view shows the firing time for each charge in each hole.

In either case (pyrotechnic or electronic), the design timing sequence should be the same (e.g. 700 ms, 725 ms, 750 ms) and the charges should be fired consecutively. For the analysis in this paper, the delay interval is always 25 ms.

Finally, Fig. 1c shows three types of detonators and two types of delay elements (pyrotechnic and electronic). In the pyrotechnic system, the delay is given by the length and burning rate of the chemical component. Therefore, varying the length of this element varies the time delay. In the electronic system, the time delay is controlled by an electronic circuit.

## 3. Experimental results of accuracy and precision of detonators

### 3.1. Statistical analysis of test results

The University of Kentucky Explosives Research Team (UKERT), through various studies, has collected data for detonator timing tests. The detail for testing follows the testing setup presented in Lusk [3]. Table 1 shows the results of testing different detonators for the delay times in the problem depicted in Fig. 1.

**Table 1**
Summary of detonator results.

| Detonator | Test results statistics of firing times | | | |
|---|---|---|---|---|
| Pyrotechnic | Random variable | $t_{25\text{-pyto}}$ | $t_{100\text{-pyro}}$ | $t_{700\text{-pyro}}$ |
| | Nominal delay (ms) | 25 | 100 | 700 |
| | Total detonators | 59 | 65 | 59 |
| | Delay average (ms) | $\mu_{25\text{-pyro}} = 27.751$ | $\mu_{100\text{-pyro}} = 102.730$ | $\mu_{700\text{-pyro}} = 715.710$ |
| | Standard deviation | $\sigma_{25\text{-pyro}} = 0.765$ | $\sigma_{100\text{-pyro}} = 11.250$ | $\sigma_{700\text{-pyro}} = 6.195$ |
| Electronic | Random variable | | $t_{675\text{-elec}}$ | $t_{700\text{-elec}}$ |
| | Programmed delay (ms) | | 675 | 700 |
| | Total detonators | | 20 | 20 |
| | Delay average (ms) | | $\mu_{675\text{-elec}} = 675.326$ | $\mu_{700\text{-elec}} = 700.220$ |
| | Standard deviation | | $\sigma_{675\text{-elec}} = 0.417$ | $\sigma_{700\text{-elec}} = 0.342$ |

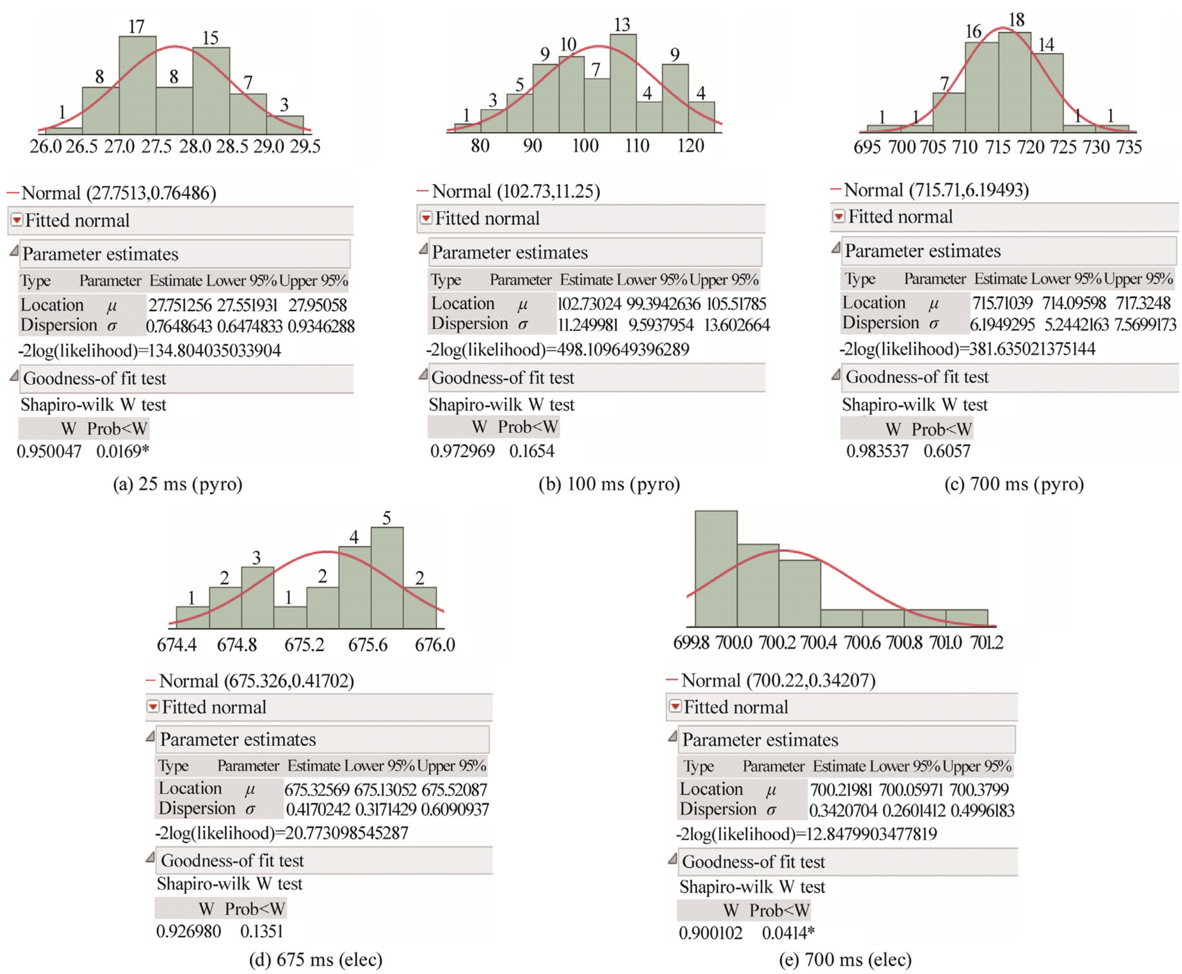



**Fig. 2.** Shapiro-Wilk test for normality (using JP® SAS software).

In this problem, the firing times of detonators are assumed to follow a normal distribution. The Shapiro-Wilk test was used to verify this assumption for the data of each delay time [4]. The results are included in Fig. 2.

For the Shapiro-Wilk test, the null hypothesis ($H_0$) is that the data is normally distributed. The chosen $\alpha$-level is 0.05. If the $p$-value is smaller than 0.05, the null hypothesis is rejected, and there is evidence that the data does not follow a normal distribution. As shown in Fig. 2, the $p$-values of tests for pyrotechnic 100 ms, 700 ms, and electronic 675 ms are greater than 0.05, so the null hypothesis of the normal distribution cannot be rejected. However, for pyrotechnic 25 ms and electronic 700 ms the $p$-values are smaller than 0.05. Thus, the null hypothesis for the two tests is rejected, and the collected data is concluded to not be normally distributed. The failure of the normality tests may be attributed to an insufficient sample size. However, for the problem under analysis, the normal distribution assumption is maintained.

### 3.2. Relationship between nominal delay and firing time scatter

For the pyrotechnic system shown in Fig. 1a, all the delay times can be achieved using connection combinations of detonators with nominal delays of 50 ms, 100 ms, and 700 ms. The test data in Table 1 is enough to analyze the system's performance in this case. However, for the electronic system in Fig. 1b, each detonator initiates each explosive charge independently, and is separately

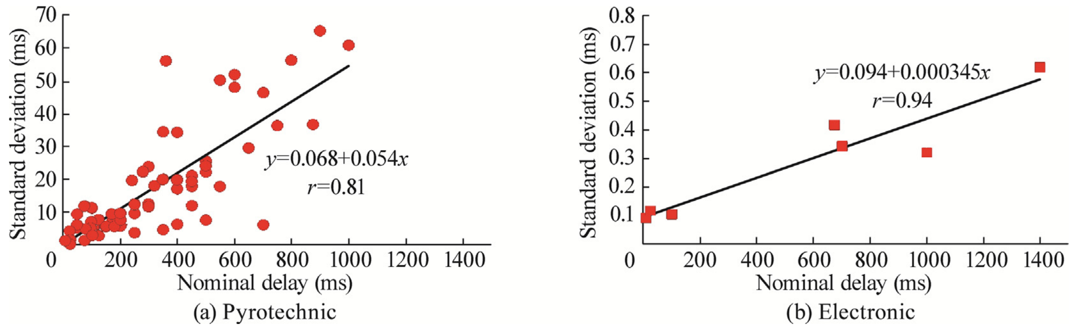



**Fig. 3.** Experimental results scatter for pyrotechnic and electronic detonators [5].

assigned to a designed delay time. Therefore, analysis of an electronic system requires statistical information for every delay time. Testing every delay time for an electronic system is cost prohibitive, and only two sets of delays for this system are included in Table 1. To provide the data for the analysis in the electronic scenario a linear regression was performed using detonator scatter information collected by UKERT over several years. The results are included in Fig. 3.

From the linear regressions in Fig. 3, it is possible to find the relationship between the standard deviation (scatter) of actual delay timing versus the nominal delay given by:

$$SD_{py} = 0.068 + 0.054t_{nominal} \quad (1)$$

$$SD_{elect} = 0.094 + 0.000345t_{nominal} \quad (2)$$

The practical use of Eqs. (1) and (2) is to estimate the variability (scatter) of any detonator's firing time from its nominal delay time. For example, if the detonator is a 700 ms delay, the pyrotechnic system will fire with a standard deviation of 37.868 ms. On the other hand, for the same nominal delay in the electronics scenario, the standard deviation is 0.336 ms.

Fig. 3 also shows that despite all the recent improvements in the accuracy of detonators (pyrotechnic and electronic), there is still variability in the delay timing of individual detonator components. The trend also shows that for both systems, the variability (scatter) is greater for high nominal delay intervals.

## 4. Outcome analysis of a single delay interval

Adjacent detonator delays are designed to fire successively by a specified delay interval. However, due to the variability of firing times (scatter), the actual delay interval may not be equal to the designed interval, and the detonation of two adjacent detonator delays can produce different outcomes. Fig. 4 analyzes different outputs (locations 1 through 5) for two adjacent detonator delays.

### 4.1. Success

For this research, the reliability of a mining blast may be defined as the probability of timing sequence success. Success may be achieved by ensuring every detonator is initiated successfully, the delay interval between any two adjacent firing times is within a certain range, and that no timing related problems are encountered.

In Fig. 4, two charges *a* and *b* are designed to fire in a given nominal delay interval. Assuming that the charge, *a* was fired at a certain time $t_a$, the charge *b* should fire after a time given by the nominal delay interval. If this is the case, it is obvious that the detonation is a success. However, as shown in Fig. 3, any detonator is subject to variability (scatter) in its firing time. Thus, a successful time delay window around the firing time of charge *b* needs to be considered in the problem.

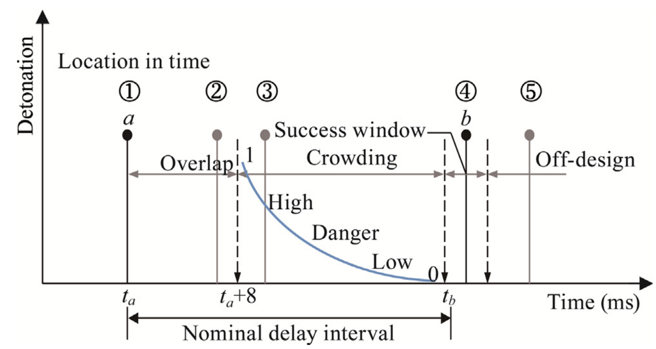



**Fig. 4.** Success, crowding, overlapping and off-design concepts [5].

How to define the success window is arbitrary, but a normal distribution with the nominal delay interval as a mean ($\mu$) and a critical variance can be adopted. The variance should be small enough to ensure the values of the delay interval fall within three standard deviations of mean (99.7%). Therefore, based on the reference distribution, the range of ($\mu - 3\sigma$, $\mu + 3\sigma$) can be defined as the success window. Any distribution with a variance smaller than the critical variance will be considered precise enough to coincide with the design. A distribution with higher variance will be considered not precise, and probabilities of unsuccessful outcomes (overlap, crowding or off-design) should be calculated.

To determine the critical variance and the standard deviation ($\sigma$) of the reference distribution, the coefficient of variation (*CV*) can be used. This parameter is used as a relative measure of the scatter of a random variable. The coefficient of variation is defined as [6]:

$$CV(x) = \frac{\sigma(x)}{\mu(x)} \times 100\% \quad (3)$$

where *x* is a random variable; *CV*(*x*) is the coefficient of variation; $\mu(x)$ and $\sigma(x)$ are its mean and standard deviation respectively.

The coefficient of variation indicates the central tendency of a distribution. A higher coefficient of variation represents greater scatter. As technology improves rapidly toward a high precision detonator, there should be a strict expectation and limitation to the scatter. Thus, for this analysis, the coefficient of variation of the reference distribution is limited to 2% for pyrotechnic and electronic systems. In other words, the standard deviation $\sigma(x)$ should be limited to 2% of $\mu(x)$.

According to Fig. 1, the designed nominal delay interval is 25 ms. Thus, the mean of the reference distribution is 25 ms, and the standard deviation is 0.5 ms. The reference distribution is shown in Fig. 5.

According to the definition of success above, the success range is $(25 - 0.5 \times 3,\ 25 + 0.5 \times 3) = (23.5,\ 26.5)$. Any delay interval of

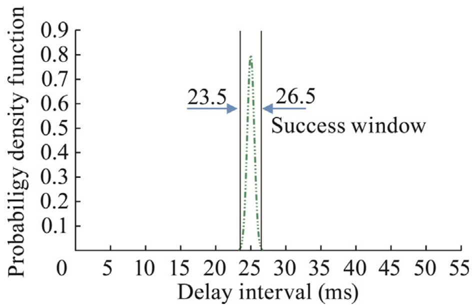



**Fig. 5.** Reference distribution and success window ($\mu = 25$, $\sigma = 0.5$).

the production shot which falls within this range is considered a success.

### 4.2. Overlapping

Overlapping is defined as the event when two adjacent detonators fire with a delay interval shorter than 8 ms (detonation of charges in locations 1 and 3 in Fig. 4). This assumption is based on the 8-ms rule specified in the federal regulations code (CFR, Title 30, §816.67), which states that all charges firing within any 8-millisecond interval will be considered as simultaneous detonation. That is, overlapping makes two charges act as one charge, which usually causes blasting performance problems such as higher ground vibration, flyrock, and airblast [7,8].

### 4.3. Crowding

If the delay interval occurs within the area between the success and overlapping regions, it is defined as crowding. The crowding area can be viewed as a transitional region between overlapping and success. It transitions from success to overlap as the value of delay interval gets closer to 8 ms. Thus, different delay interval values in the transition region of crowding should be weighted according to the varying degree of risk.

A curve with values ranging from 0 to 1 can be fitted to the crowding region to represent the degree of risk [5]. Zero is assigned to the lower limit of the success window (no risk), and level of risk increases to 1 at a delay interval of 8 ms. The curve is shown in Fig. 4, and it will be used in the risk analysis.

### 4.4. Off-design

It should also be noted that detonation beyond the success time window is undesirable. This scenario is called off-design. It may generate problems for the next delay interval. Therefore, for risk analysis of a single delay interval, the effect of off-design is not taken into account, as it will be included in the risk analysis of the next delay interval.

## 5. Reliability block diagram in terms of delay interval

In reliability engineering, there are several system modeling schemes used to perform analyses. These include, among others, reliability block diagrams, fault tree and success tree methods, event tree methods, failure mode and effect analyses, and master logic diagram analyses (Modarres[9]). Due to its relative simplicity, the reliability block diagram method was used in this paper. A Reliability Block Diagram (RBD) performs the system reliability and availability analyses on large and complex systems using block diagrams to show network relationships. The structure of the reliability block diagram defines the logical interaction of failures within a system that is required to sustain system operation. The rational course of an RBD stems from an input node located at the left side of the diagram. The input node flows to arrangements of series or parallel blocks that conclude to the output node at the right side of the diagram. A diagram should only contain one input and one output node. The RBD system is connected by a parallel or series configuration, or a combination of both.

### 5.1. Timing arrangement for pyrotechnic system

The block diagram's derivation of the pyrotechnic timing sequence configuration (Fig. 1a) is based on the timing arrangement presented in Fig. 6.

In Fig. 6, the blast is configured from left to right with three rows of four holes each. The first level is the original connection of detonators and their corresponding nominal delays. The second tier is the desired (designed) firing time for each charge. Mathematically, the firing time of each detonator may be thought of as an independent random variable. Thus, the firing time for each charge is also an independent random variable because it is a linear combination of a certain number of single detonators. According to the illustration in Fig. 6, every charge firing time may be expressed by a linear combination of $t_{25}$, $t_{100}$, and $t_{700}$. One thing to notice is that the values of $t_{25}$, $t_{100}$, and $t_{700}$ are different and independent for different detonators and charges because they are different random variables. Subscripts are used to distinguish these variables. For convenience, let $i$ denote the row number, $j$ denote the $j$th charge in the $i$th row, and $t_{i,j}$ denote the firing time of the $j$th charge in the $i$th row. Then each firing time ($t_{i,j}$) can be written as:

$$\begin{cases} t_{i,j} = \sum_{m=1}^{2i-2} t_{100,m} + \sum_{n=2}^{j} t_{25,i,n} + t_{700,i,j} & \text{for } 1 \leqslant i \leqslant 3,\ 1 \leqslant j \leqslant 8 \\ \sum_{m=1}^{2i-2} t_{100,m} = 0 & \text{for } i = 1 \\ \sum_{n=2}^{j} t_{25,i,n} = 0 & \text{for } j = 1 \end{cases} \tag{4}$$

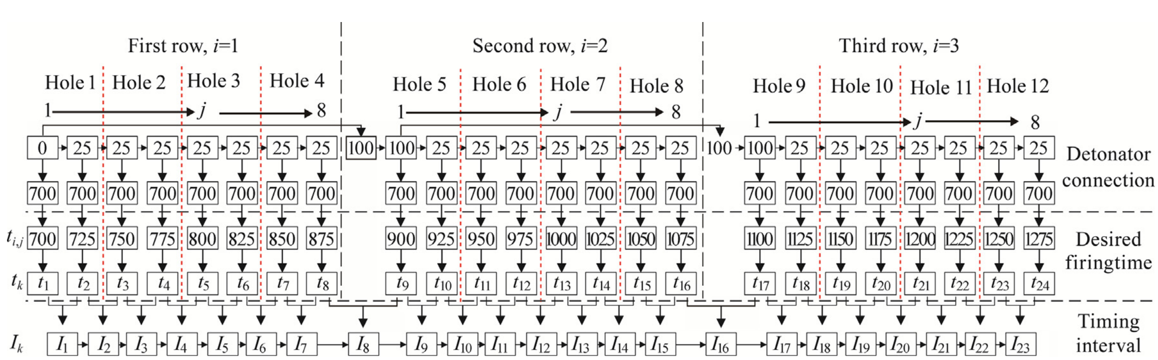



**Fig. 6.** Timing arrangement for pyrotechnic system.

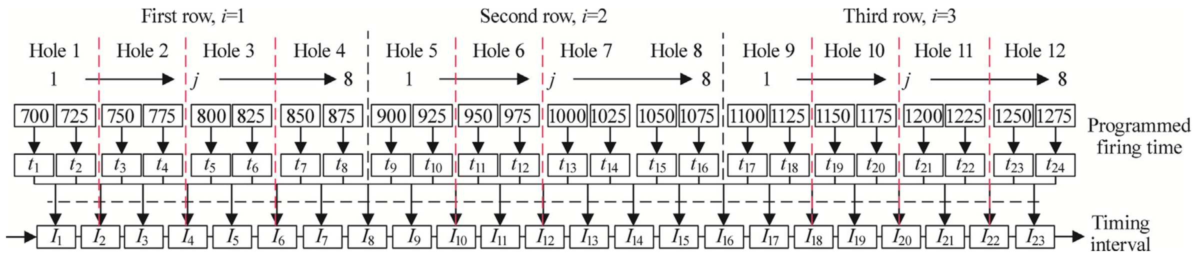



**Fig. 7.** Timing arrangement for electronic system.

In Eq. (4), $t_{100,m}$ denotes the firing time of 100 ms detonators which make the row-to-row delay; $t_{25,i,n}$ denotes the surface delay which corresponds to the $j$th charge in the $i$th row; and $t_{700,i,j}$ denotes the in-hole delay which corresponds to the $j$th charge in the $i$th row. The first summation in Eq. (4) is actually the time shift from row to row; the second summation is the cumulative surface delay for the $j$th charge in the $i$th row; and the third term represents the in-hole delay for the $j$th charge in the $i$th row. The last two terms together comprise the incremental change in delay time from charge to charge in each row.

### 5.2. Timing arrangement for electronic system

The timing arrangement for the electronic system is included in Fig. 7.

In this situation, every firing time is programmed for each detonator, so each firing time is independent and can be written as:

$$t_{i,j} = t_{delay,i,j} \tag{5}$$

### 5.3. Block diagrams for pyrotechnic and electronic systems

The analysis included in this paper is based on the success or failure of two consecutive charges. For the numerical example developed here, the "ideal" delay interval of two charges is 25 ms. In Figs. 6 and 7 the time between two charges is shown in the last level of the diagrams (timing interval level). If all the firing times ($t_{i,j}$) are sorted by order of incremental time, and are labeled as $t_k$ where $k$ is the charge number with $1 \leq k \leq 24$, then $t_{i,j}$ and its corresponding $t_k$ are indicated in Figs. 6 and 7. For such a case:

$$k = 8(i-1) + j \tag{6}$$

Taking the difference between two adjacent firing times results in delay intervals ($I_k$), which is also a random variable. The value of $I_k$ consists of the last level in Figs. 6 and 7 and is given by:

$$I_k = t_{k+1} - t_k \quad 1 \leqslant k \leqslant 23 \tag{7}$$

As mentioned before, a RBD performs the system reliability and availability analyses on large and complex systems by showing network relationships between system components (in this case the delay interval, $I_k$). The structure of the reliability block diagram defines the logical interaction of failures within a system that are required to sustain system operation.

The following definitions are established to apply reliability engineering concepts to this problem: the system is the entire production blast, every delay interval between charges ($I_k$) is a block of the RBD, and the failure of the whole system could have different definitions according to the definition of success.

The last point is important for the reliability analysis, and there are many options for the definition of the failure of the whole system. Some of these definitions are classified in Table 2.

According to reliability engineering basics, a parallel system is defined as a system such that "at least one of the units must succeed for the system to succeed" [9]. This condition is not entirely applicable to the analysis of this problem, because if just one charge detonation fails, the whole production shot may still be considered a failure. The analysis of the maximum number of failures allowable in a parallel physical connection (electronic system) is beyond this paper. For reliability analysis comparison purposes between both systems, the analysis included in this paper is carried out assuming that all charges should detonate in an accurate and precise manner.

In Table 2, for scenario $A$, modeling the RBD in series and comparing how the physical system connection works for pyrotechnic detonators is a perfect match. If one of the charges fails, the rest of the shot will also fail. According to reliability engineering concepts, such a system is classified as a series system [9]. The RBD representation of pyrotechnic systems is based on the timing sequence as shown in Fig. 8.

The $B$ scenario definition fits the manner in which electronic detonator systems work. In such cases, the physical failure of one of the components does not compromise the success of the whole system. However, the failure of one delay interval still makes the timing sequence unsuccessful, and the reliability in terms of this failure or success is the actual objective of this analysis. Thus, in this case, the RBD blocks for the electronic connection should still be considered a series system.

To determine if each block (RBD component) is successful and what its probability of success is, the distribution of every $I_k$ is needed. As mentioned before, $I_k$ is also a linear combination of different random variables. According to statistical theories, a linear combination of independent random variables is also a random variable [10]. In other words, if $X$, $Y$, etc., are independent random

**Table 2**
Classification of failures.

| Definitions | | Success of the system from the point of view of the timing sequence, for reliability analysis ($A$ component of the system is a delay interval. RBD is in series. One component fail, timing sequence fail) |
|---|---|---|
| Physical failure of the system (System is the whole blast. $A$ component of the system is a detonator) | Connection in series. One component fail, blast fail | $A$, Pyrotechnic detonators arrangement in this paper |
| | Connection in parallel. All components fail, blast fail | $B$, Electronic detonators arrangement in this paper |

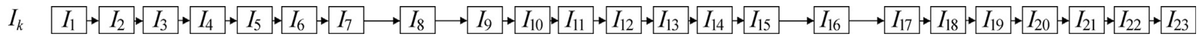



**Fig. 8.** Reliability block representation under analysis.

variables, $a$, $b$, etc., are numbers and $L = aX + bY + \ldots$, then $L$ is also a random variable, and its mean, $\mu(L)$, and standard deviation, $\sigma(L)$, can be written as:

$$\begin{cases} \mu(L) = a\mu(X) + b\mu(Y) + \ldots \\ \sigma(L) = \sqrt{a^2\sigma^2(X) + b^2\sigma^2(Y) + \ldots} \end{cases} \tag{8}$$

For the particular problem in this paper, $a = b = \ldots = 1$ or $-1$. Note that all delay times with the same nominal delay are independent identically distributed (IID) normal variables. That is, $\mu_{700,i,j} = \mu_{700}$, $\sigma_{700,i,j} = \sigma_{700}$, $\mu_{25,i,j} = \mu_{25}$, $\sigma_{25,i,j} = \sigma_{25}$, and $\mu_{100,m} = \mu_{100}$, $\sigma_{100,m} = \sigma_{100}$.

Combining Eqs. (3)–(7) and the IID theory, the statistical parameters for every $I_k$ can be written as:

$$\mu_k = \begin{cases} \mu_{25} & k \in [1, 23],\ k \neq 8, 16 \\ 2\mu_{100} - 7\mu_{25} & k = 8, 16 \end{cases} \tag{9}$$

$$\sigma_k = \begin{cases} \sqrt{2\sigma_{700}^2 + \sigma_{25}^2} & k \in [1, 23],\ k \neq 8, 16 \\ \sqrt{2\sigma_{700}^2 + 2\sigma_{100}^2 + 7\sigma_{25}^2} & k = 8, 16 \end{cases} \tag{10}$$

Eqs. (7)–(9) are applicable for pyrotechnic initiations. In the case of electronic systems, assuming that every $I_k$ follows the distribution given for the interval between electronic delays of 675 ms and 700 ms, the distribution for electronic systems are given by:

$$\mu_k = \mu_{700} - \mu_{675} \tag{11}$$

$$\sigma_k = \sqrt{\sigma_{700}^2 + \sigma_{675}^2} \tag{12}$$

The distributions of every delay interval can be calculated and are represented in Fig. 9, using the data from Table 1 and Eqs. (8)–(11).

Fig. 9 shows that electronic initiation has both small bias error and scatter in delay interval ($I_k$) compared to pyrotechnic initiation for different linear combinations of delays. Pyrotechnic initiation exhibits poor performance in these two aspects. Among the pyrotechnic delay intervals, $I_8$ and $I_{16}$ have a bias error as large as $25 - 11.203 = 13.797$ ms, and the standard deviation is even larger than the mean value. These large errors may be expected to cause problems in the system performance.

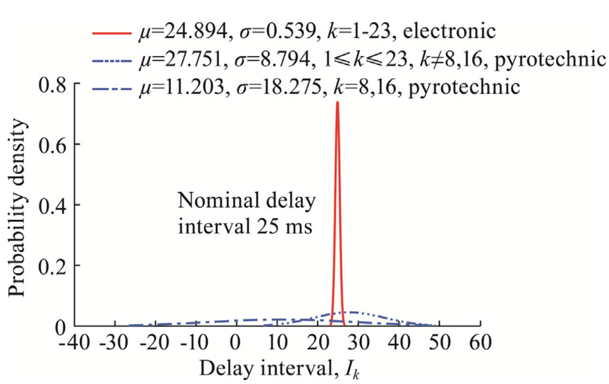



**Fig. 9.** Distribution of delay intervals.

## 6. Probabilistic risk analysis for a single delay interval

Now that the outcomes of a detonation between two adjacent charges have been clearly defined, it is possible to perform a risk analysis for the unsuccessful outcomes. Eq. (13) is a quantitative representation of risk by defining a set of triplets [11].

$$Risk = \{< s_i, p_i, x_i >\} \quad i = i, 2, \ldots, N. \tag{13}$$

where $s_i$ is an unsuccessful outcome of delay interval (overlapping or crowding); $p_i$ is the probability of that outcome; $x_i$ is the severity of problem for that outcome; and $N$ is equal to 2 in this problem (two outputs; overlapping or crowding).

Although the outcome of a delay interval is classified into different categories, the value of delay interval in each outcome region is continuous, and thus every value of delay interval may result in a slightly different severity of the problem. Thus, the severity should become a continuous variable, $x$. When the probability density function for a delay interval is used in the analysis, the probability also becomes to a continuous variable, $p$. So, the risk curve can rewritten as:

$$Risk = \{< s_i, p, x >\} \quad i = i, 2. \tag{14}$$

where $p$ is equal to the probability density function of delay interval; $x$ is assigned with a degree of risk in the crowding area ranging from 0 to 1, and a value of 1 is assigned to the entire overlap region (green line in Fig. 10). Fig. 10 shows the probability density function and the triplets defined by Eq. (14).

Using Fig. 10, the risk curve can be calculated as the cumulative distribution function for $P\ (X \geq x,\ 0 \leq x \leq 1)$ for the two different detonator systems (shown in Fig. 11).

## 7. Reliability analysis for the whole mine blast

It is necessary to evaluate reliability for a single block or component of a system (in this case the delay interval between two adjacent firing times) in order to assess reliability of the entire system. As mentioned before, reliability is defined as the probability that an item or system will perform its required function under given conditions for a stated time interval. Thus, the analysis of reliability must be accompanied by the definition of mission duration, the operating conditions, and the required function (failure definition) of the product [12].

For items like electronic elements and mechanical components, lifetime models (the time that any manufactured item can be expected to be "serviceable") using parameters such as mean time

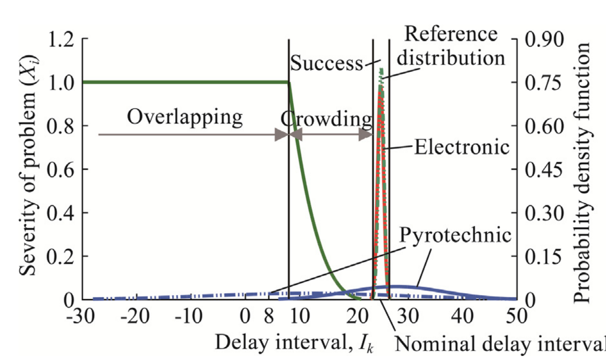
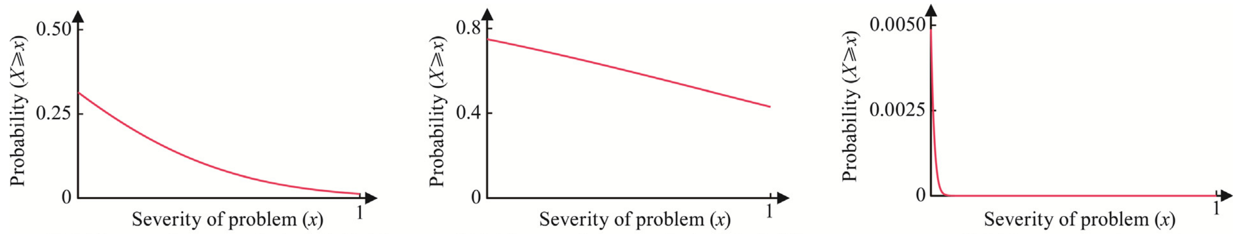



**Fig. 10.** Illustration of risk triplets.



(a) Risk curve for pyrotechnic $I_k$ ($k \neq 8$, 16) (b) Risk curve for pyrotechnic $I_k$ ($k$=8, 16) (c) Risk curve for electronic

**Fig. 11.** Risk curves.

between failures (MTBF) and failure rate are suitable to quantify the reliability. These kinds of items ("products") usually have a long lifetime and operating duration. However, detonators and explosives are classified as so-called "one-shot" items, which can only be used once. During use, the items are destroyed. One-shot items mainly spend their life in dormant storage or standby state [13]. In the timing sequence system of a production blast, a single component is a delay interval between two adjacent firing times, and its mission duration is only a brief moment (milliseconds). Hence, in this scenario, it is better to define the timing reliability of a component (delay interval) as the probability of success based on the scattering of the firing times. If the distribution of delay interval is already known, it is easy to calculate the success probability.

Operating conditions including temperature and humidity, may influence the performance of the item [14]. Thus, operating conditions should be clarified before conducting any reliability analysis. For the detonators under analysis in this paper, the operating conditions are specified as normal-range, within which the detonators work well (e.g. temperature below 40 °C, tolerant humidity, and intact detonators). Because the influence of operating conditions on reliability is not within the scope of this paper, all detonators are assumed to function under the same operating conditions.

The definition of the required function (failure definition) must also be specified. Under the operating conditions defined in this paper, the required function of a component (delay interval, $I_k$) is that its value should be within the success window defined previously. The remaining ranges outside the success window can be viewed as failure. Failure can be further divided into three failure modes: overlapping, crowding and off-design. Thus, the boundaries for success and each failure mode in the distribution of delay interval can be set as ($-\infty \leftarrow$ overlapping $\rightarrow$ 8 ms $\leftarrow$ crowding $\rightarrow$ 23.5 $\leftarrow$ success $\rightarrow$ 26.5 $\leftarrow$ off-design $\rightarrow \infty$). Based on the range classifications, the probabilities of success (reliability) and each failure mode can be calculated as the area under the probability distribution curve (PDF curve) within each range. The calculation results are summarized in Table 3.

According to the results above, for pyrotechnic detonators the probability of success of the individual system blocks is given by $R(I_k) = 0.1290$ when $k \in [1, 23]$ and $k \neq 8$, 16, and $R(I_k) = 0.0492$ when $k = 8$, 16. For electronic detonators, the same parameter is given by $R(I_k) = 0.9937$ for every $I_k$. The results show that electronic initiation has much higher reliability in timing performance than pyrotechnic initiation (highest probability of about 11%). The result is that electronic initiation when analyzed as individual components of the mining blast is found to be about 9 times more reliable (successful) than pyrotechnic initiation.

**Table 3**
Reliability and failure probabilities of component.

| Component state | Probability | | |
|---|---|---|---|
| | Pyro, $k \neq 8$, 16 | Pyro, $k = 8$, 16 | Elec, $k \in [1,23]$ |
| Overlapping | 0.0124 | 0.4304 | 0.0000 |
| Crowding | 0.3021 | 0.3191 | 0.0049 |
| Success | 0.1290 | 0.0492 | 0.9937 |
| Off-design | 0.5566 | 0.2013 | 0.0014 |

Production blasting mission duration is defined as the time interval from start to the end in a given timing sequence network. Generally speaking, the mission duration is very short (usually seconds) compared to the lifetime of a detonator (several years). The operating condition is the same as what has been discussed in the preceding section. When analyzed from the RBD as above, the components (delay intervals) are connected in series. Every component is assumed to be an independent variable with a normal distribution. For a series system, success only occurs when every part is successful. System reliability can be calculated from component reliabilities and is given by:

$$R = \prod_{k=1}^{Q_p} R_k \tag{15}$$

where $R$ is the reliability of the system; $Q_p$ is the number of components; and $R_k$ is the component reliability. A series system always has less reliability than its components (because $R_k \leq 1$). In the case under analysis we have:

$$R(system) = R(I_1) \ldots R(I_k) \ldots R(I_{23}) = \prod_{k=1}^{23} R(I_k) \tag{16}$$

where for pyrotechnic initiation, $R(system) = \prod_1^{23} I_k = 0.1290^{21} \times 0.0492^2 = 5.08 \times 10^{-22} \approx 0$; for electronic initiation, $R(system) = \prod_1^{23} I_k = 0.9937^{23} = 0.8647$.

The results above indicate the pyrotechnic timing system is not reliable for the required functions. On the other hand, the reliability of electronic initiation is 0.8647, which is not ideal but greatly improved over pyrotechnic initiation.

A real danger in production blasting is presented by the failure mode of overlapping. Crowding may also present a high risk if the delay interval approaches 8 ms. Attention should thus be given to the occurrence levels of overlapping, crowding, and off-design among all the delay intervals in a production blast. Distributions of these occurrence times are also helpful for engineers in learning about the behavior of timing sequence systems influenced by detonator firing time scatter and bias. To obtain a useful estimate of the occurrence times, Monte Carlo simulation (MCS) is an effective method of dealing with the complexity of this problem.

## 8. Monte Carlo simulation of system behavior

Monte Carlo simulation is a powerful tool for analyzing complex systems due to its capability of achieving a close adherence to reality. It is a method for estimating problems using random numbers [15].

According to the previously discussed analysis, the probability of every failure mode for each $I_k$ is already known. Among the $N$

($N = 23$) independent trials (explosive charges), the distribution of occurrence times $x$ ($0 \leq x \leq N$) of a failure mode is the purpose of Monte Carlo simulation. The probability of $x$, $P(x)$, is derived from the concept of relative frequency probability. Thus, every delay interval can be treated as a random repeatable trial. This means the combination, expressed as the entire production blast, is also random and repeatable. For every single delay interval trial, the outcomes of each individual failure mode (e.g., overlapping, crowding, off-design) only contains "yes" or "no". In each iteration of Monte Carlo simulation, the number of "yes" results are counted among the total 23 trials. After repeating the simulation a large number of $L$ times, and counting the number of "yes" results each time, the ratio of occurrence ("yes") times $x$ to $L$ is the probability of $x$.

The Monte Carlo method used in this paper was implemented in Microsoft Excel, and was divided into steps as follows [16]:

(1) Generate a set of random numbers (23) with uniform distribution within (0, 1). These numbers are taken as the Cumulative Distribution Function (CDF) for each delay interval $I_k$. The function used is *RAND* ( ).
(2) Based on the previous results, the CDF for every $I_k$ is known. Taking the inverse computation of CDF, a possible outcome of delay interval can be obtained by its corresponding CDF value. This method can generate a sample set for a production blast which contains 23 outcomes. The samples are obtained for both pyrotechnic and electronic detonators. The function used was NOM.INV (probability, mean, standard deviation).
(3) Count the occurrence times of each failure mode, denoted by $x_{overlap}$, $x_{crowding}$, $x_{\text{-}design}$. Restore the numbers and one iteration of the simulation is completed.
(4) Repeat the simulation $L$ times, which represents a long run condition. Here, let $L = 20{,}000$.
(5) Count how many times each $x$ value appears, and they are expressed by $l(x = 0)$, $l(x = 1)$, ..., $l(x = 23)$.
(6) The probability of $x$ can be calculated by Eq. (17). Moreover, a distribution of $x$ can be obtained.

$$p(x) = \frac{l(x)}{L} \tag{17}$$

The simulation results are shown in Fig. 12. These results indicate overlapping phenomena for pyrotechnic initiation is most likely to happen for one out of the 23 delay intervals. The probability is 0.4458. The second most probable overlapping numbers are 0 and 2, with probabilities of 0.2562 and 0.2442, respectively. The other occurrence times are of low probability with a decreasing trend when $x$ increases.

The distribution of crowding occurrence levels is similar to a bell shape, with a mean of approximately 7 times. This result means the crowding occurrence level is mainly between 5 and 9 times. Similarly, the occurrence level of off-design also follows a bell-shaped distribution with the values concentrated between 10 and 15. Note that the reliability of the pyrotechnic timing system is 0, which is consistent with the involute of different kinds of failure modes. However, the numbers of overlapping and high-risk delay intervals are not as large as expected even if $R$ is 0.

The situation for electronic initiation is different. There is a 100% probability of overlapping not to occur (0 times) in a production blast. Even for crowding and off-design events, the expected value is nearly 0. Although the reliability of the system is only 0.8647 due to a narrow success range, the system performance is satisfactory.

## 9. Discussion

The research in this paper has demonstrated the influence of firing-time scatter on a production blast outcome.

There are different methodologies to control ground vibration from blasting using the optimum delay interval between consecutive blast charges such as signature-hole method/linear superposition [17–21]. When an optimal delay interval has been determined, the ideal expectation is for all charges to fire exactly as determined by the design timing sequence. Any significant error of firing time for even one hole may result in a failure of implementation of the optimum timing design. This situation requires the detonators to have extremely high accuracy and precision in delay periods. According to the findings of this paper, electronic initiation systems should be used to ensure this level of control. The same findings indicate pyrotechnic detonators are not sufficiently reliable to provide the proper delay interval needed when ground vibrations are a concern for mining operations.

The existing literature about timing error and overlap problems in mining blasts are all based on the premise that success is simply non-reversal in timing, or the delay interval is larger than 8 ms. This paper introduces in a novel quantitative approach the concepts of overlapping, crowding, success, and off-design for the analysis of mining blasts. Also, crowding is associated with different levels of risk using the concept of triplets and weighing the severity of the problem from 0 to 1 in the crowding zone of the problem.

For computation convenience, the firing times of pyrotechnic detonation are assumed as independent. In reality, due to the complexity of the timing network, the firing times are not independent. Studies on the dependence of firing times and the weighting function of the severity of the problem for the risk analysis in the crowding zone will be included in future research.

## 10. Conclusions and future work

It is helpful to analyze the system performance of timing sequences based on overlapping phenomena. Reliability is used to examine the performance of the system (the production shot). The degree of reliability of the system is mainly influenced by

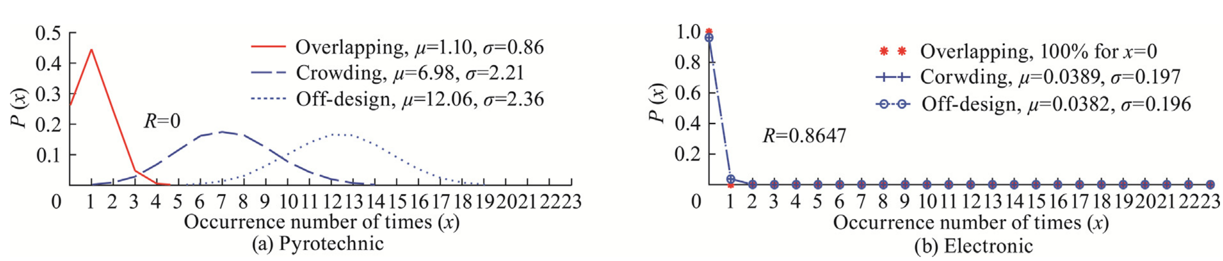



**Fig. 12.** Monte Carlo simulation analysis results.

scattering and bias error of firing times. The lower the scatter and bias, the higher the reliability of the system. For pyrotechnic initiation, the reliability is poor and is close or equal to zero. The reliability of the electronic initiation timing system is 0.8647. It is obvious that the electronic timing sequence arrangement yields much better results than the pyrotechnic arrangement.

For individual delay intervals, pyrotechnic initiation has greater scatter and bias error compared to electronic initiation, which contributes to the high probability of failures and low chance of success. For the delay interval connecting the last and first charges in two rows, the pyrotechnic detonators have very large scatter and bias error, and the standard deviation is larger than the mean value.

Regardless of how the timing network is organized, the detonations must occur in a specified sequential order. This characteristic makes the system (known as a mining production shot) progress in series on the level of delay interval from a reliability block analysis point of view. Thus, the calculation of reliability is simply the product of each of the delay reliabilities. However, the determination of each delay interval's distribution may be complex due to different series or parallel connections of detonators.

From the results of Monte Carlo simulation, it is concluded that with a reliability of zero, the failure of pyrotechnic timing sequence system is a mixture of overlapping, crowding, and off-design. Overlapping and crowding phenomena may account for less than 3 delay intervals in one production blast but will be recurring events in blasting.

A normal distribution was used as a reference to specify the success range. It is independent of the data of both types of detonators and can be applied to specify the success window for any delay intervals. In future research, more field tests will be conducted to analyze the quantitative relationship between different delay intervals and blasting performance problems to allow for more meaningful and practical risk analyses.

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